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Research article

Exploring the dynamics of research collaborations by mapping social networks in invasion science

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ABSTRACT

Moving towards more integrative approaches within the invasion sciences has been recognized as a means of improving linkages between science, policy, and practice. Yet despite the recognition that biological invasions pose complex social-ecological challenges, the invasion literature poorly covers social-ecological or distinctly integrative research. Various initiatives and investments have been made towards building research capacity and conducting more integrative research aimed at improving the management of biological invasions. Using a combination of social network and thematic analysis approaches, and the South African Working for Water (WfW) program as a case study for the management of invasive species, we identify and explore the roles of core authors in shaping collaboration networks and research outputs, based on bibliographic records. We found that research produced under the auspices of WfW is authored by a handful of core authors, conducting primarily ecologically-focused research, with social research significantly underrepresented. Core authors identified in this study play an essential role in mediating relationships between researchers, in addition to potentially controlling access to those seeking to form collaborations, maintaining network cohesion and connectivity across institutional and disciplinary boundaries. Research projects should be designed to span disciplines and institutions if they are to adequately address complex challenges.

1. Introduction

Invasive alien species (IAS) are whose ranges have been either accidentally or purposefully altered by humans resulting in self-replacing populations over several life cycles capable of spreading over large areas in their new habitat (Richardson and Pysek, 2010; Richardson and Rejmánek, 2011). The negative impacts of invasive species on biodiversity, livelihoods and ecosystems have been increasingly recognized across the globe (Buch and Dixon, 2009; van Wilgen and Richardson, 2012; Dickie et al., 2014; Vaz et al., 2017a). This increased recognition is evidenced by the prevalence of dedicated journals (such as *Biological Invasions* and *NeoBiota*), regular conferences (such as NeoBiota- International Conference on Biological Invasions and EMAPI- International conference on Ecology and Management of Alien Plant Invasions), and the establishment of centres of excellence (such as Centre for Invasion Biology) (van Wilgen et al., 2014) concerned with invasion research. While research on invasive species and their management is growing, it is still mostly disciplinary (Vaz et al., 2017a). The rapid pace, complexity, and scale of challenges associated with biological invasions, have led to increased calls for integrative research approaches, such as those offered by multi, inter and transdisciplinary research methodologies (Jerneck et al., 2011; Ntshotsho et al., 2015; Vaz et al., 2017a).

More integrative approaches in invasion science have the potential to enhance linkages between science, policy, and practice through improved stakeholder engagement and grounding of research in social processes, making research more relevant and salient to implementers (Cowling et al., 2008; Lang et al., 2012; Richardson, 2011; Ntshotsho et al., 2015). Yet despite biological invasions being increasingly recognized as a social-ecological phenomenon, it has been shown that integration between social and ecological systems are not easily observed in research or practice (McNeely, 2001; Estevez et al., 2014; Head et al., 2015; Hui and Richardson, 2017). Vaz et al. (2017a) suggest that invasion science be reframed to allow for the formation of research teams that comprise a balance of social scientists and natural scientists with shared strategies for conducting research. The establishment of long-term, reciprocal relationships for engaging multiple stakeholders (academic and non-academic), addressing conceptual questions and research problems, and the implementation of collaborative approaches (epitomized by inter-or transdisciplinary research) have been argued for, both in invasion science and other disciplines

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dealing with complex environmental sustainability issues (Spangenberg, 2011; Lang et al., 2012; Tengo et al., 2014; Turner et al., 2016; Vaz et al., 2017a).

Integrative research is influenced by several institutional factors including research policy and funding structures, governance systems, and institutional arrangements geared towards collaborative research (Mollinga, 2010; Sandstrom and Rova, 2010; Jahn et al., 2012; Tengo et al., 2014; Nel et al., 2016). Differences in organizational architecture (including but not limited to organizational policies, governance and mandate), research capacity, resource availability (including facilities, funding, human resources, collaboration networks) and research focus, locate certain organizations and individuals in optimal positions to facilitate integrative research (Rafols et al., 2010; Lyall and Fletcher, 2013; Kabo et al., 2014). Researchers or institutions with an inclination to work across disciplinary boundaries play key roles in the integrative research process and potentially, the facilitation of integrative research (Lyall et al., 2013; Esler et al., 2016). Evidence exists about the importance of core researchers—that is, researchers who maintain a field and enable its continued existence through driving research agendas (Gordon, 2007) – in influencing knowledge production, and the development and growth of research collaboration networks in their respective disciplines or fields (Gordon, 2007; Wagner and Leydesdorff, 2005).

Core researchers can leverage social and other resources (such as financial, technical, equipment, and expertise) in such a way that these can either encourage or inhibit integrative research and innovation (Li et al., 2013). Established researchers therefore play a role, not only in building a knowledge base, but also in facilitating the integration of new knowledge therein by way of leveraging resources (Brandes, 2001; Wagner and Leydesdorff, 2005; Li et al., 2013). Three dimensions to social resources (or capital) that can facilitate the development of intellectual resources, have been proposed, specifically: structural, relational, and cognitive capital (Nahapiet and Ghoshal, 1998). Structural capital refers to structural embeddedness, such as network ties, configuration and density of connections amongst individuals. Relational capital refers to the assets (e.g. trust, commitment, and reciprocity within the group) people create and leverage through personal relationships, and with which they change behaviours and fulfil social motives, such as sociability, approval and prestige (Tsai and Ghoshal, 1998). Finally, cognitive capital refers to those resources an individual develops over time as they interact with others sharing understanding and expertise, learning skills, knowledge and specialized discourse and forming the norms of practice for the collective (Li et al., 2013). Each of these dimensions constitutes an aspect of the collaboration network structure that can facilitate the integration and exchange of knowledge amongst individuals within the network (Li et al., 2013).

Research funders also play important roles in facilitating integrative research initiatives. For example, funding organizations can stimulate integrative research by identifying questions that require inter-disciplinarity and specify the inclusion of an inter-disciplinary team to provide the optimal solution (Cornell et al., 2013; Kabo et al., 2014; Turner et al., 2016). This in turn may lead to the creation of new funding schemes where funders may have a role in the establishment of the architecture of an integrative research program, through the choice of leadership, location, streams of funding, and mechanisms for accountability (Lyall et al., 2013). Funders also play a role in research capacity building through the provision of infrastructure and funding to create institutions. The combination of these various aspects may in turn facilitate the emergence of longer term impacts from the funded research (Rafols et al., 2010; Lyall et al., 2013). Therefore, it is important to explore the role and impact of funding institutions in shaping research initiatives.

Since its establishment in 1995, a South African government initiative, the Working for Water (WfW) programme, has made significant financial contributions towards the management of invasive alien plants (IAPs) (Bennett and van Sittert, this issue). The mandate of WfW is to recover ecosystem services being lost to IAPs, while also empowering individuals through job creation and community building and conserving biological diversity, ecological integrity and catchment stability (Common Ground, 2003; van Wilgen and Wannenburgh, 2016). The financial investment from WfW includes research funding aimed at improving the understanding IAP impacts and building the evidence for best management practices to improve IAP control (Macdonald, 2004; WfW, 2005; van Wilgen and Wannenburgh, 2016). Thus, WfW significantly influences research through its funding contributions and collaborations with research organizations and can be considered an important driver of IAP management related research, both in South Africa and globally.

Accordingly, the aim of this paper is to identify and explore the roles of researchers in shaping collaboration networks and associated research outputs, by mapping the co-authorship network that developed within the WfW funding context. Core researchers were identified and their role and influence on network structure, evolution and knowledge production explored (Rafols et al., 2010; van der Valk and Gijsbers, 2010; Mingers and Leydesdorff, 2015). Social network analysis (SNA) enables the identification of key actors who could potentially improve research integration across disciplines.

2. Methods

2.1. Identification of research articles

We identified peer-reviewed articles (excluding book chapters and conference proceedings) published between 1995 and 2017 produced under the auspices of the Working for Water programme, more specifically articles funded or co-funded by WfW. Thomson Scientific's Web of Science (WoS) was subjected to keyword searches of funding text, title, abstract and keyword fields. Funding text fields were searched using the following terms: “working for water”; “wfw”; “working-for-water”; “working for water program*”. Outputs from known WfW co-funded initiatives were also included through search phrases, such as “research for integrated management of invasive alien species”, a collaborative research project by the DST-NRF Centre of Excellence for Invasion Biology (the Centre for Invasion Biology or C·I·B), the South African National Biodiversity Institute's “invasive species programme”, and the Agricultural Research Council's “weed biocontrol capacity building initiative”. However, due to known limitations such as the poor coverage of funding acknowledgements prior to 2009 (Paul-Hus et al., 2016), the following search terms were used to capture articles that may have been missed when searching only funding texts: “invas*” and “plant*”; “alien* and “plant”; “invas*” and “ecolog*”; “invas*” and “ecolog*” and “manag*”; “invas*” and “ecolog*” and “policy”; “invas*” and “ecol*” and “implement*” (adapted from Esler et al., 2010).

The resultant bibliographic records' funding texts were then checked manually to confirm WfW as a funding source. Where no funding information was available in bibliographic records obtained from WoS, full-texts were obtained and checked manually. Articles where funding texts did not clearly indicate WfW or a known co-funded initiative were omitted from results. A total of 364 articles (after omissions) published from 1997 to 2017 were identified and catalogued.

Information about each of the resulting articles was obtained from WoS and assembled in a database. Information in the database included unique identifiers for individual articles, authors, their affiliations, funding organizations and thematic information. Records obtained from WoS were checked manually to ensure that variations of author and institution names were accounted for and unified before analysis.

2.2. Thematic analysis

Articles were subjected to thematic analysis, a research method well-suited to the study of communications (Elo and Kyngas, 2008). The

latent content of the articles was coded by reading each article in its entirety and making an overall assessment of its primary emphasis, using an inductive coding approach. Through a process known as abstraction, article level themes were merged into higher order themes that describe larger sets of articles (Elo and Kyngas, 2008). Each article was assigned to a single, most appropriate theme.

2.3. Mapping of research articles, researchers and research topics

We used Gephi 0.9.1, a freeware network analysis and visualization package (Bastian et al., 2009), to present the research collaboration networks associated with the WfW programme, based on the bibliographic data obtained from WoS. We identified and mapped the relationships between articles and authors, and included the use of co-publication, co-authorship, and bimodal graphs to show the relationship between authors and research themes. Co-authorship networks represent social structures made up of individuals called nodes, which are connected by one or more specific kinds of interdependency represented by links (also called ties, edges or connections). Simply put, nodes are symbolic references to individuals (hereon referred to as authors) and their relationships (links) to one another. In the co-authorship networks presented in this study, links between authors indicate that they have co-authored an article (publication) together (i.e. they have authorship in common). The co-publication network is its inverse, wherein links represent common authorship. The ForceAtlas2 continuous graph layout algorithm, used to enhance network spatialization and visualization designed for the Gephi software, was used to generate the maps (Jacomy et al., 2014). This technique allows for a visual interpretation of the network structure and is used to turn structural proximities (based on the ties or connections between nodes) into visual proximities, facilitating the analysis of social networks. Noack (2009) and Jacomy et al. (2014) show that force directed layouts as generated by ForceAtlas layouts optimize the visualization and identification of communities (closely related authors), where communities (authors with more links in common) appear as groups of nodes (authors) (Jacomy et al., 2014).

2.4. Identification of core authors

We used three approaches to identify core authors, namely a thematic analysis to identify authors' primary research areas and those who publish across themes, centrality metrics (degree, eigenvector, and betweenness), and the classification of authors based on their publishing behaviour (Price and Gursey, 1976). Based on these three approaches we generate networks to both analytically and visually locate core authors and research communities. To simplify the visualization, we include only authors that form part of the main component of the network, i.e. the largest connected cluster in the network. This eliminates both isolates (solitary unconnected authors) and small detached clusters of authors. Most network measures are based on the main component which functionally represents the largest subset of individuals that are connected to one another through both direct and indirect paths (Powell et al., 2005). In this study, the main component combines each year's set of authors (1997–2017) and includes 574 of the 610 authors identified. These main authors were responsible for the co-authorship of 345 articles.

Using Gephi we identified core authors by calculating three individual author centrality measures i.e. degree centrality, Eigenvector centrality and betweenness centrality. Degree centrality measures the frequency of connections that tie authors to their co-authors based on bibliographic records. High degree centrality indicates that the author is connected by many links in an unweighted network. In a weighted network, a high degree implies large flow to and from an author (e.g. information) (Chopra and Khanna, 2014). Eigenvector centrality is the measure of an author's influence in a network, based on the centrality measures of neighbouring authors (Bonacich, 2007). The higher the degree centrality of an author's co-author, the higher that author's Eigenvector measure and centrality will be. Strong ties to other central authors provide them with access to a rich source of information and competitive advantage in the network (Bonacich, 2007). Betweenness centrality is how often an author lies on the shortest path between other authors in a collaboration network (Brandes, 2001). Authors with high betweenness scores represent those who control information flow between authors in the network; the higher their score the greater their influence in the network. In addition to calculating author betweenness scores, we calculated the betweenness centrality for the links, to identify the most important links in the network.

To represent authors' published contributions over time we used a scheme by Price and Gursey (1976) who placed authors into one of four categories based on their publishing behaviour, namely: continuants (authors who publish before, during and after a given year), newcomers (those who publish during and after a given year), terminators (those who publish before and in a given year), and transients (those who publish only in a given year) (Wagner and Leydesdorff, 2005). Continuants are considered core authors in a field as they tend contribute articles regularly, before and after research in a field is at its peak, in addition to maintaining continuity in the network and field (Wagner and Leydesdorff, 2005; Gordon, 2007). The years 2004 and 2011 were selected for this analysis, as both saw a significant increase in research article publishing in the field of invasion research (see Appendix A).

3. Results

3.1. Author affiliation and institutional relationships

Six-hundred-and-ten authors contributed to the 364 articles across 91 journals, published over the period of 1996–2017. Sixty-seven percent of the articles were co-authored exclusively by authors affiliated to South African institutions. Ninety-nine percent of articles were co-authored by at least one author affiliated to a South African institution and 28% by at least one internationally affiliated author. We identified 228 affiliated institutions, of which 49 (21.5%) are South African. The most substantial contributions were made by a handful South African institutions across the country (Table 1). Collaborations between Stellenbosch University (SU), the South African National Biodiversity Institute (SANBI) and the Council for Scientific and Industrial Research (CSIR) resulted in the authorship of 211 articles of which eight involve an affiliate of each institution. Stellenbosch University and SANBI-affiliated authors collaborate closely with one another (Fig. 1) and collectively account for at least 76 articles. Collaborations between SU and the CSIR have resulted in 192 articles of which 32 involved at least one author from each institution. Of the 610 authors, 440 (72.1%) published in only one given year, of which 396 (co)authored only one article. Forty authors (6.5%) identified as being affiliated with the Agricultural Research Council (ARC) have (co)authored 76 articles. Authors affiliated with the Centre for Invasion Biology (C·I·B) (co)authored 179 (49.2%) of the articles in the dataset. The C·I·B, headquartered at SU, represents an affiliation of authors from several institutions. Though the clear majority of C·I·B affiliates are based at SU, several of them hold multiple affiliations including to other universities, the CSIR and SANBI amongst others.

3.2. Thematic analysis

Through thematic analysis, a total of eight themes were identified (Table 2). Research topics focused primarily on invasion dynamics and distributions (28,9%) and biological control (34,9%), with economic, hydrological and socially-focused research being less frequent (Table 2). The co-publication network shows that biological control research forms a separate and looser (low density) grouping from the invasion-restoration-management research cluster (which is denser, with more authors in common), with which it has relatively few authors

Table 1
The contribution made by research organizations to the authorship of individual articles based on research associated with the Working for Water programme published between 1997 and 2017. Number of authors represented by these organizations are reported, with the number of authors working across research themes shown in brackets.

Organizations	Country	Articles[a]	No. of authors
Centre for Invasion Biology (C·I·B)[b]	South Africa	179	87 (49)
Stellenbosch University (SU)	South Africa	165	105 (42)
South African National Biodiversity Institute (SANBI)	South Africa	97	48 (14)
Agricultural Research Council (ARC)	South Africa	76	40 (4)
Rhodes University (RU)	South Africa	69	44 (5)
Council for Scientific and Industrial Research (CSIR)	South Africa	52	32 (9)
University of Kwa-Zulu Natal (UKZN)	South Africa	49	38 (1)
University of Cape Town (UCT)	South Africa	42	21 (6)
University of Pretoria (UP)	South Africa	30	18 (4)
University of Witwatersrand (Wits)	South Africa	24	17 (6)
Charles University, Prague	Czech Republic	11	15 (2)
Commonwealth Scientific and Industrial Research Organisation	Australia	10	12 (1)
Academy of Science Czech Republic	Czech Republic	10	10 (3)
Nelson Mandela Metropolitan University (NMMU)	South Africa	10	11 (4)

[a] Minimum of 10 articles.
[b] The C·I·B, headquartered at Stellenbosch University, represents an affiliation of authors from multiple institutions (including those in the table above).

in common (Fig. 2). Furthermore, within the biological control research grouping, there exists several smaller clusters with relatively few connections between them. These clusters are distinct, appear to be drawn along institutional lines (Fig. 2) and are characterized by authors who have published frequently (Table 2). Economic, hydrologically and socially-focused research is largely peripheral, sharing few authors with the invasion-restoration-management research and biological control clusters. The majority of single, two or three-author articles cover research primarily focused on biological control, whereas multi-authored articles are more associated with ecological and management related research.

Authors publishing in the applied research areas of management and implementation, and restoration, have a greater percentage of authors working across disciplinary boundaries, as opposed to those publishing in biological control and hydrology (Table 2). Of the 110 authors working across research themes (the majority of whom are affiliated with SU and the C·I·B), only 47 have published across three or more of the research themes (Fig. 3), with the remaining authors only publishing across two research areas. Of those working across three or more research themes, the majority are C·I·B affiliates based at SU, the CSIR and SANBI (Fig. 3).

3.3. Centrality measures

We found that C·I·B affiliates based at primarily at SU and the CSIR, have co-authored the articles (42.8%), particularly D.M. Richardson (27%) (Table 3). The twenty most productive authors are responsible for the co-authorship of 72% of the total articles studied. These authors have also collaborated with a higher number of co-authors (high degree centrality) (Table 3 and Fig. 4). In terms of Eigenvector centrality, we find that close neighbours of top ranking authors (degree centrality) have higher scores, irrespective of the number of articles they have authored. Instead the higher the number of high ranked (degree centrality) authors they are connected to, the more highly they will be ranked in eigenvector centrality.

Betweenness measures clearly highlight leaders among co-authors in the network, indicating those who control information flow between, or connect otherwise disparate clusters of, individuals (Fig. 4). The highest scoring individuals are well ahead of those who follow them (Table 3). More senior or established authors in the network provide the shortest path for most of their immediate neighbours. These central authors lie on the paths between themselves and the rest of the network in most instances. This holds true for established authors in the biological control community. Ties between central authors tend to score most highly in terms of link (edge) betweenness scores (Fig. 4), which suggests that should these links be severed, it will most likely disrupt the flow of information and other resources in the network.

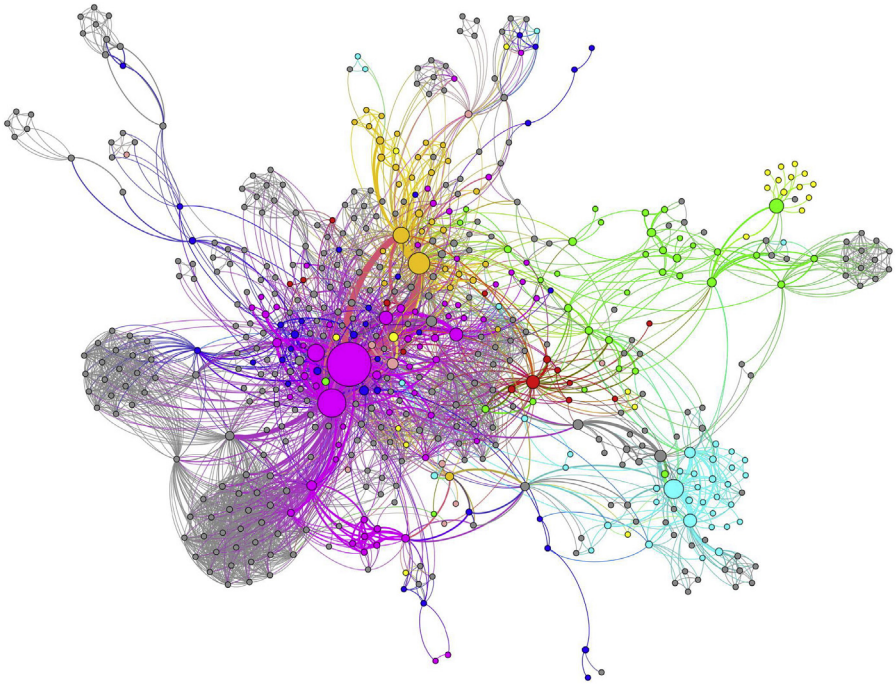

Fig. 1. Co-authorship map of Working for Water associated authors. Node size is representative of the number of articles produced by the author. Node colour is representative of author affiliations. Links between nodes indicate that authors have co-authored an article together. Wider links are indicative of a higher frequency of co-authorship. Only the top eight organizations (most affiliated authors) are colored. Purple- Stellenbosch University, green- ARC, light blue- Rhodes University, yellow- University of KwaZulu-Natal, orange- CSIR, red- University of Cape Town, light pink- University of Pretoria, and blue- SANBI. The Centre for Invasion Biology (C·I·B), headquartered at Stellenbosch University, represents an affiliation of authors from multiple institutions, so is not reflected in this graph. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 2
Description of research themes, including percentage of articles in each category (n = 364), the number of authors and the core authors associated with a research theme, and the number and percentage of authors working across thematic categories.

Research theme	Description of research themes	Node colour (see Fig. 2)	% Articles	No. of authors	No. of authors working across disciplines	Core authors (no. of articles)
Biocontrol research	Deals with biocontrol and discussing management pros and cons and suitability for release	Red	34,89%	148	37	Olckers, T (23) Hoffmann, JH (17) Hill, MP (31)
Invasion research	Focuses on definitions, concepts, mechanisms, new introductions, distribution, abundance, demography, and synergistic effects associated with invasives (that is research relating to invasion dynamics)	Green	33,.51%	237	90	Richardson, DM (50) Wilson, JRU (43) le Roux, JJ (26)
Management and implementation research	Discusses the management of invasives and the outcomes of management activities with a particular emphasis on operational and policy interventions	Light blue	9,61%	163	60	Richardson, DM (18) Van Wilgen, BW (14) Wilson, JRU (12)
Restoration research	Discusses both active and passive restoration and rehabilitation in relation to invasions	Orange	7,42%	50	25	Richardson, DM (11) Esler, KJ (12) Holmes, P (12)
Economic research	Deals with economic aspects of the program, including feasibility studies, cost-benefit analyses, valuations and pricing estimates	Yellow	3,57%	43	14	Van Wilgen, BW (9) Marais, C (3) Blignaut, J (3)
Hydrological research	Discusses the hydrological impacts associated with invasions (e.g. IAP water use, surface water yield and river flow response)	Blue	3,85%	38	11	Le Maitre, DC (7) Dzikiti, S (6) Gush, M (5)
Social research	Discusses the human dimensions associated with IAP management, including job creation, poverty relief and livelihoods	Purple	3,02%	44	24	Richardson, DM (5) Prozesky, H (2) Shackleton, RT (2)
Ecological research	Deals with ecological studies not directly related to invasive alien plants	Grey	4,12%	40	22	Weyl, OLF (4) Zengeya, TA (4) Booth, AJ (4)
Total			100%			

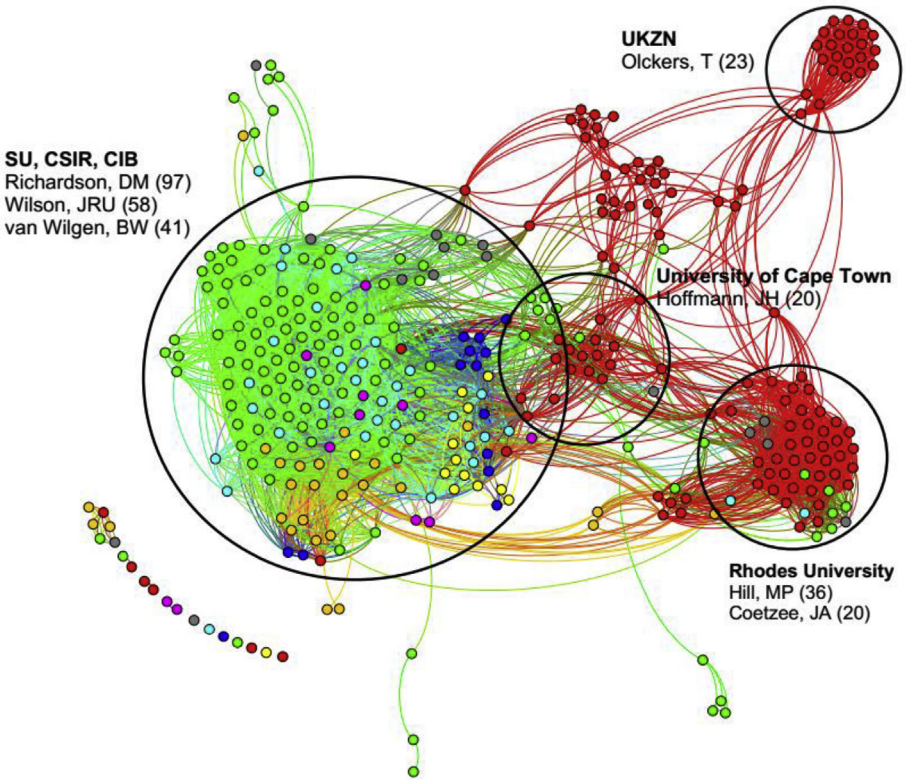

Fig. 2. Co-publication network of research produced under the auspices of the Working for Water programme. Articles are categorized according to their primary research theme (colour codes explained in Table 2). Nodes and links represent articles and common authorship between articles. Circled areas highlight key research subcommunities in the network. The adjacent text indicates the primary institutions (in bold) to whom the research can be attributed to, as well as the authors responsible for most articles in the respective communities. (SU- Stellenbosch University, CSIR- Council for Scientific and Industrial Research, C·I·B- Centre for Invasion Biology, UKZN- University of Kwa-Zulu Natal). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

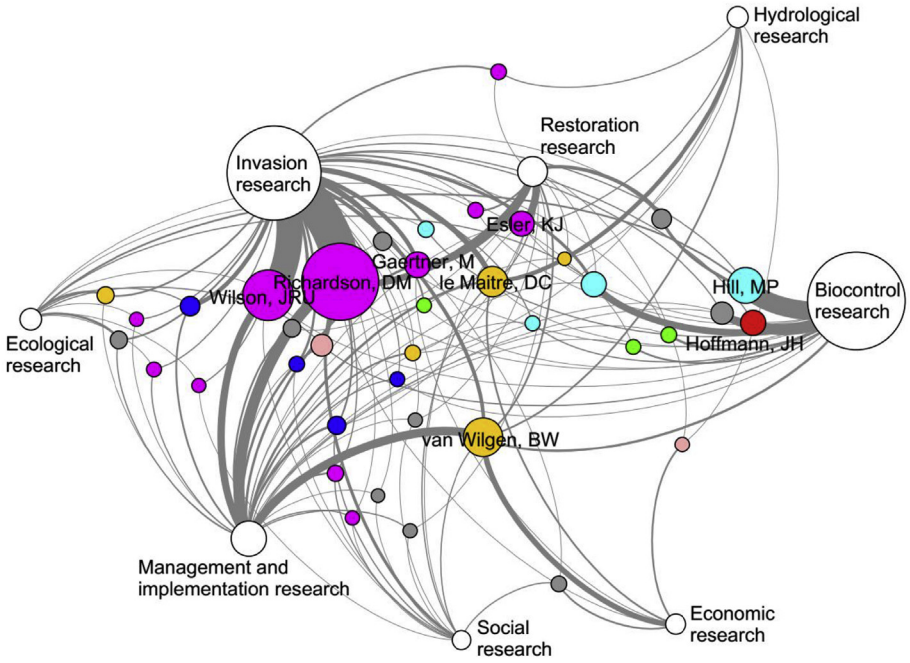

Fig. 3. A bimodal graph illustrating the links between the primary research areas and authors with at least three articles across three research themes. White nodes represent research areas, coloured nodes, authors. Only the top eight organizations (with the most affiliated authors) are coloured. Purple- Stellenbosch University, green- ARC, turquoise- Rhodes University, yellow- University of KwaZulu-Natal, orange- CSIR, red- University of Cape Town, pink- University of Pretoria, and blue- SANBI. Node size is proportionate to the number of associated articles. The link width is representative of the number of times an author has published in the area. Only authors that have co-authored at least 20 articles are labelled. The Centre for Invasion Biology (C·I·B), headquartered at Stellenbosch University, represents an affiliation of authors from multiple institutions, so is not reflected in this graph. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 3
Author rank based on centrality measures. Higher values mean a higher rank. Authors in bold are those who have authored or co-authored at least 10 articles. Authors marked with an asterisk are C·I·B associates that are not C·I·B core researchers. C·I·B core research team (2017) members are italicized.

Rank	Label	No. of articles	Label	Degree centrality	Label	Betweenness centrality	Label	Eigenvector centrality
1	***Richardson, DM***	97	***Richardson, DM***	252	***Richardson, DM***	0,345289	***Richardson, DM***	1
2	***Wilson, JRU***	58	***Wilson, JRU***	149	***Wilson, JRU***	0,122607	***Wilson, JRU***	0,735565
3	***van Wilgen, BW***	41	***van Wilgen, BW***	96	***van Wilgen, BW***	0,098644	Pysek, P*	0,53156
4	**Hill, MP**	36	**Le Maitre, DC***	78	**Hoffmann, JH**	0,096345	Brundu, G	0,483001
5	***Le Roux, JJ***	30	Pysek, P*	76	**Le Maitre, DC***	0,090525	***Kumschick, S***	0,451003
6	**Le Maitre, DC***	28	***Le Roux, JJ***	73	***Robertson, MP***	0,069891	Kuhn, I	0,413754
7	**Olckers, T**	23	***Kumschick, S***	64	**Zachariades, C**	0,066792	Schindler, S	0,409233
8	**Gaertner, M***	21	Brundu, G	59	**Hill, MP**	0,061361	Blackburn, TM*	0,404485
9	**Coetzee, JA**	20	**Hoffmann, JH**	57	***Le Roux, JJ***	0,052349	Essl, F*	0,401898
10	***Esler, KJ***	20	Marchante, E	55	**Coetzee, JA**	0,043144	Bacher, S	0,392447
11	**Hoffmann, JH**	20	**Gaertner, M***	51	**Olckers, T**	0,039752	Roques, A	0,388683
12	***Byrne, MJ***	16	Blackburn, TM*	49	Weyl, OLF	0,039377	Rabitsch, W	0,387465
13	***Robertson, MP***	15	***Esler, KJ***	48	Blignaut, J	0,03933	Hulme, PE	0,385296
14	**Paterson, ID**	14	Zenni, RD	46	McConnachie, AJ	0,038855	Genovesi, P	0,385296
15	**Holmes, PM***	13	Pauchard, A	46	Renteria, JL	0,036714	Nentwig, W	0,385296
16	***Kumschick, S***	12	Kuhn, I	45	**Witkowski, ETF**	0,033403	Vila, M	0,385296
17	**Witkowski, ETF**	12	**Hill, MP**	44	Neser, S	0,033013	Jeschke, JM	0,385296
18	**Novoa, A**	10	Schindler, S	44	Canavan, K	0,031114	Pergl, J	0,385296
19	**Rouget, M**	10	Kull, CA	43	**Gaertner, M***	0,029429	Kenis, M	0,382944
20	**Zachariades, C**	10	Essl, F*	41	***Esler, KJ***	0,02745	Gallardo, B	0,380775

3.4. Research continuance

Using the categorization scheme proposed by Price and Gursey (1976), we identified several core authors to understand research continuance. We selected two years (2004 and 2011) that represent distinct peaks in publication output and assessed new entrants (authors) to the network and number of collaborations (ties) established between authors (Appendix A). The publication peaks are attributed to WfW (co) funded journal special issues in the *South African Journal of Science* (2004), *Diversity and Distributions* (2011) and *African Entomology* (2011), as well as the establishment of the C·I·B in 2004. Six core authors (continuants) were common to 2004 and 2011 (Fig. 5), and they (co)authored 41% of all articles studied. Of the 50 newcomers to the network between 2004 and 2011, 28 became established as continuants by 2011 (Fig. 5). Continuants identified in relation to 2004, were responsible for 17 (68%) of the articles published up to and including 2004. These 2004 continuants account for 37 (50%) of the articles up to the end of 2010, and 119 (41%) of those published from 2011 onwards. Continuants identified in relation to 2011 were responsible for the co-authorship of 165 (78%) articles published after 2004, and 34 (77%) of those from 2011. Collectively, continuants (relative to 2004 and 2011) account for 81% of all articles (involving at least two continuants) studied. Continuant authors tend to co-author articles with one another (Fig. 5), further suggesting that relations amongst newcomers and transients are mediated by continuants.

4. Discussion

South Africa is one of a handful of regions globally where researchers producing highly cited articles in invasion ecology are well represented (Pyšek et al., 2006). Invasion ecology is one of the most productive scientific disciplines in South Africa, both in terms of the number of published articles and its global citation footprint (Pouris, 2006, 2007). Our aim was to identify and explore the roles of

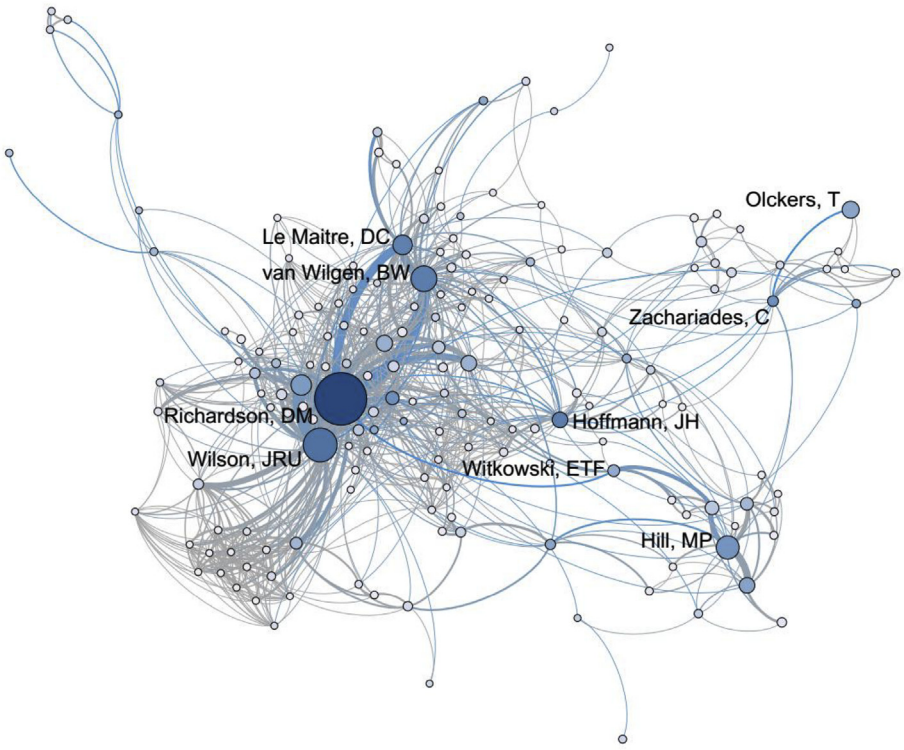

Fig. 4. Co-authorship network of WfW associated authors. Node size represents degree centrality (larger nodes = higher scores). Node color is representative of betweenness centrality scores, darker shades of blue equals higher scores. Wider links are indicative of a higher frequency of co-authorship. The links with a high betweenness are represented by darker shades of blue, whereas grey represents those with lower scores. Nodes with a betweenness score of zero were omitted. 168 nodes are presented. Core authors are labelled, with emphasis on those with high betweenness scores. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

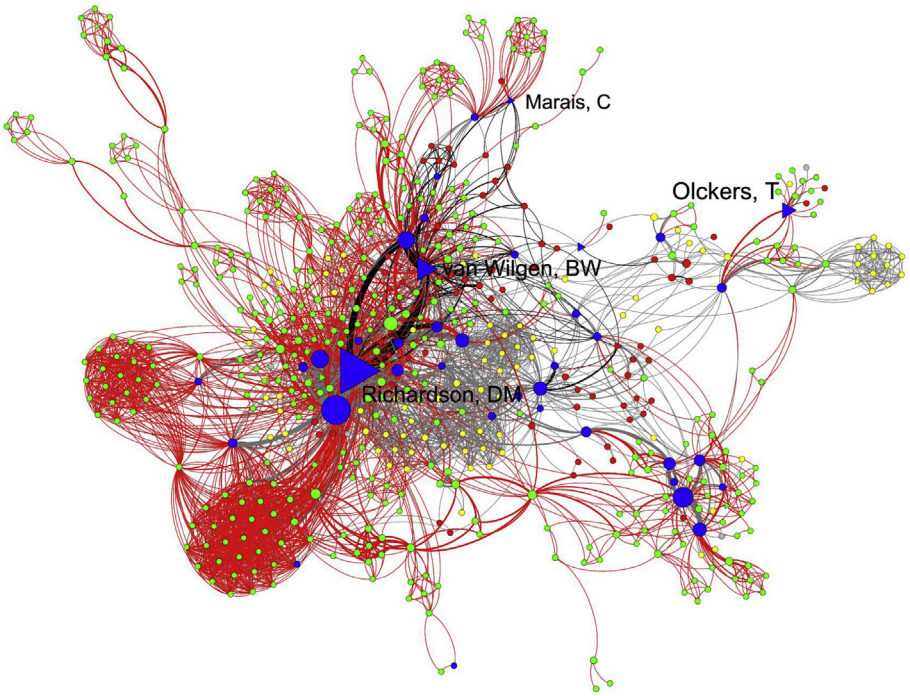

Fig. 5. Co-authorship network of WfW associated authors. Blue nodes represent continuant authors, green-newcomers, red-terminators, and yellow-transients, in relation to 2011 peak. Link color represents when links were formed. Wider links are indicative of a higher frequency of co-authorship. Black links were established between 1997 and 2004, grey-2005-2011 and red-2012-2017. Triangular nodes represent continuant authors in the 2004 peak. Links between red nodes and their neighbors represent ties that were established and then severed over the 1997 to 2011 period. The more articles co-authored by an author the larger the node. Continuants common to both 2004 and 2011 peaks are labelled. (See Appendix A2 for counts of continuant, newcomers, terminators and transient authors for each year). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

researchers in shaping collaboration networks and associated research outputs within invasion ecology context. Specifically, we focused on mapping the co-authorship network that developed within the funding context of Working for Water (WfW), an important driver of invasive alien plant management related research, both in South Africa and globally.

Invasive species can contribute to people in both beneficial (such as medicine, secondary industries, agroforestry, reduced harvesting pressure on native species) and potentially harmful ways (such as diminished water resources, diminished agricultural potential of landscapes), which requires them to be actively monitored and managed (Kull et al., 2011; Shackleton et al., 2015; Vaz et al., 2017b; Kull et al., this issue; Shackleton et al., this issue). However, due to the conflicts of interest around who bears the costs and who benefits (from IAPs), the different management techniques to control invasions and the diversity of actors involved (Novoa et al., 2016; Shackleton et al., this issue), the management of invasions is inherently complex (Kueffer, 2013; Vaz et al., 2017a; Shackleton et al., this issue). Any research geared towards providing input to the management of invasive species must account for this complexity. Research that is inclusive of diverse disciplines and

knowledge systems has been shown to better address and inform management issues as it can surface local contexts that can inform more nuanced decision making (Novoa et al., 2016; Kueffer, 2013; Ntshotsho et al., 2015). An improved understanding of how authors and their collaboration networks are structured allows us not only to identify potential actors who can lead or co-design and facilitate research activities, but also highlights the risks and potential consequences associated with the removal of key individuals (or institutions) from collaboration networks (Borgatti, 2006). We found that research produced under the auspices of WfW is authored by a handful of core authors who conduct primarily ecologically-focused research, with socially relevant research significantly underrepresented. We used SNA to identify spaces where integration between disparate knowledge domains (with respect to research collaboration) can occur within the broader management of biological invasions and related areas such as ecological restoration.

It is important to note that we sourced our information from WoS which is one of the most comprehensive bibliographic databases to include broad scale indexation of funding information post 2008 (Paul-Hus et al., 2016). However, the lack of broad-scale indexing of funding information prior to 2008 (Paul-Hus et al., 2016), meant that many articles funded by WfW may have been excluded and as stated in our methods, we manually checked articles for which no bibliographic record of funding information was provided.

4.1. Core authors

Research outputs associated with the WfW programme are authored primarily by a small group of core authors that have provided sustained research contributions on a continual basis over extended periods. This finding is consistent with other studies that looked at the publishing behaviour of researchers (Wagner and Leydesdorff, 2005; Gordon, 2007; Huang, 2014). The core group of continuants primarily authored ecologically focussed research with social and economic sciences less well represented. While there are continuants contributing to social research, there is no clearly identifiable core of social science researchers sustaining research over extended periods of time. The core authors identified in this study seldom appear as solo authors. The tendency of continuants to collaboratively produce articles increases not only their productivity, such as publishing more articles, but also their connectivity with other authors within the network. Continuants play important roles in mediating relationships between co-authors, including newcomers and transients entering the network (Wagner and Leydesdorff, 2005). Therefore, the longer they remain active by publishing articles and collaborating on research, the greater the likelihood that they will co-author articles with a greater diversity of researchers, thereby expanding the collaboration network in their field or area of interest (Braun et al., 2001; Wagner and Leydesdorff, 2005).

4.2. Expanding collaboration networks

Improved understanding of how research network expansion occurs and how collaborations form can allow for more effective management of the network structure to maximize research benefits, which can include increased integration of knowledge across and beyond disciplinary boundaries and increased research productivity (Borgatti and Foster, 2003; Wagner and Leydesdorff, 2005). Jeong et al. (2001) show that evolving networks conventionally grow through two processes, the addition of new authors (typically in the form of accumulative advantage) and through new links developing between existing authors (e.g. reinforcement of advantageous relationships or homophily). Our findings for the WfW context suggest that accumulative advantage has occurred as evidenced by the high proportion of new connections between continuants and new entrants to the network (Fig. 5) (Jacomy et al., 2014) over time. These authors are typically at the centre of a network or community and have a high number of connections (degree centrality), because of their sustained research contributions (Powell et al., 2005; Abbasi et al., 2011, 2012). More senior (or published) authors typically benefit from accumulative advantage, as they often possess privileged social and technical insights that are desirable to newcomers and transients seeking access to this information and acquire thus recognition within their field. Continuants therefore gain greater productivity and credibility in their field (Bala and Goyal, 2000; Wagner and Leydesdorff, 2005). How continuants leverage their advantageous position can impact both research and governance outcomes within their specific contexts. If influential individuals or groups in the network are oblivious to the need for or unwilling to participate in collaborative activities, they may likely, whether knowingly or not, block the initiatives of other participants inside and outside the network (Wagner and Leydesdorff, 2005; Serenko and Bontis, 2016).

4.3. Network homophily

Our results also suggest a level of homophily which is signified by an increased density of authors and stronger connections between them (Fig. 4) - where the sharing of ideas occurs primarily between individuals who share similar interests and who know and trust each other (McPherson et al., 2001; Huang, 2014; Kadushin, 2011; Wald et al. this issue). These collaborations also tend to be self-reinforcing, thereby perpetuating and stabilizing collaborations and resulting in knowledge exchange, building and strengthening of capacity (Borgatti and Foster, 2003; Huang, 2014). This self-reinforcement of the collaboration network is observed in this study particularly amongst authors affiliated with the CSIR and SU, following the establishment of the C·I·B in 2004 (Fig. 1). Frequent co-authorship (Fig. 4) amongst C·I·B affiliates (Table 3) accounts for a substantial proportion of articles produced by authors in the collaboration network. These affiliates were identified as core authors across centrality and continuance metrics.

Although information spreads more efficiently in a homophilous network and among members with strong ties to one another through a greater frequency of collaborations, there are risks associated with excessive homophily. Such risks may negatively affect research productivity by hampering knowledge cross fertilization and research innovation that might have occurred through interacting with new researchers, disciplines or institutions, thereby perpetuating the same information. The risk is that this information may become redundant, reducing adaptability to fast changing research environments (Katz and Martin, 1997; McPherson et al., 2001; Huang, 2014). Our study confirms that challenges relating to biological invasions have been framed primarily in terms of the natural sciences, with social science research being underrepresented (Kueffer, 2013, Table 2). For researchers to cope constructively within increasingly complex research environments, there is a need to assimilate a diversity of knowledge from a wide range of disciplines including knowledge that is not organized in disciplinary terms (Jerneck et al., 2011; Esler et al., 2016). This is particularly true for those engaging in interdisciplinary or management-oriented research which seeks to address the complex social-ecological challenges associated with biological invasions (Kueffer, 2010, 2013; Shackleton et al., this issue).

4.4. The role of key central authors

The centrality of an author can also be seen as the extent to which an individual connects to those who would not otherwise be connected. In SNA this is often quantified using the betweenness centrality metric (Abbasi et al., 2012; Badar et al., 2015). Individuals who score highly in terms of this metric, often act as bridges (brokers) between otherwise separate sets of authors (Bodin and Crona, 2009). Our results show that while there is a strong clustering amongst co-authors of invasion, restoration, and management and implementation-oriented research (particularly amongst C·I·B affiliates, SU and the CSIR (Figs. 1 and 2)), the same cannot be argued for the biological control research

communities. These communities are not well connected to one another, but also to the remainder of the WfW funded research collaboration network (Fig. 3). This suggests the presence of structural holes or gaps, exhibited by the absence of links connecting otherwise unconnected clusters of authors. Here, individuals that can bridge these gaps could gain a position of advantage to exchange information and mediate benefits that could be shared across this gap such as (such as technical and financial resources) (Burt, 2004). Structural holes exist because people tend to focus on endeavours inside their own groups, which creates gaps in the flow of information between groups (Burt, 2004). The loss of authors with high betweenness scores, either through becoming fully disconnected, or more weakly connected, could result in the loss of information, resources and other benefits they offer to the network (Borgatti, 2006). For example, the loss of key authors (scoring high in terms of betweenness) (Fig. 4) linking the biocontrol community to the invasion-management-restoration community, has the potential to significantly influence the flow of knowledge between these research communities.

The value of highly connected authors in boundary spanning activities between disciplines and in linking subgroups of authors in collaboration networks has been shown in several disciplines, including socio-ecological (Jerneck et al., 2011; Turner et al., 2016), natural resource management (Bodin et al., 2006; Bodin and Crona, 2009), research administration (Huang, 2014) and organizational science (Ruef, 2002). Such knowledge brokers can facilitate the integration of information across a large knowledge pool (Bodin et al., 2006). Through an in-depth knowledge of specific research domains and an understanding of where certain expertise is held within a network, these knowledge brokers can mobilise collaborative efforts to achieve a particular objective (Nel et al., 2016; Sitas et al., 2016).

4.5. Implications for research and management

Researchers are incentivized to work collaboratively for several reasons, including but not limited to: increased access to resources, such as funding, facilities and ideas, greater likelihood of being cited for enhanced research impact (Li et al., 2013), and international diplomacy (Adams, 2012). Bodin and Crona (2009) argue that working collaboratively also leads to increased likelihoods for joint action, enhanced knowledge development and understanding through increased access to information and exposure to new ideas. This is advantageous when addressing complex research issues especially since collaborations are essential to sustainable knowledge creation, reducing cost and optimizing resource use, and may enable intellectual companionship of researchers (Huang, 2014).

To overcome barriers to knowledge integration and innovation, and the poor connectivity between disparate groups, strategic engagement by actors in the network is required (Sunderland et al., 2009). Actors in a network should purposively seek to engage with collaborators outside their immediate community if the research is intended to have action on the ground. In the WfW context, this requires increased collaborations between social and natural scientists, as well as non-academic stakeholders (such as practitioners) throughout the research process. The core authors identified in this study are optimally positioned to guide future research efforts and to initiate inter-disciplinary collaborations towards addressing the challenges associated with IAPs. The formulation of a research agenda in collaboration with core researchers, funders and managers could aid such efforts.

If a greater number of social ties are established in a network, more opportunities for joint action and collaborative efforts would exist. These opportunities would potentially help to avoid conflicts between researchers or institutions over financial, institutional and human resources. It has been argued that strong links between stakeholders (both academic and non-academic) can foster community resilience and increase the adaptive capacity for environmental change. This requires a dynamic balance between bonding (homophilic) and bridging links (Tompkins and Adger, 2004; Newman and Dale, 2005). For example, within the WfW context, extending outside the community by establishing bridging links to facilitate greater engagement with the social sciences and non-academic stakeholders in the research process is a good start. Setting up bonding links within the WfW context, can encourage greater collaborative effort between biological control research (e.g. UKZN, Rhodes University and the ARC), invasion and restoration research communities (e.g. SU, CSIR and C·I·B).

Decision-makers, funders and research organizations can have a major impact on how research is shaped, including the extent and effectiveness of integration (Lyall et al., 2013). This is especially true for integrative research, where through their funding mechanisms, framing of research questions and agendas, and relationships between them, funders can influence the nature of research initiatives and its relevance to decision making processes (Lyall et al., 2013; Cornell et al., 2013; Turner et al., 2016).

Although considerable progress has been made in terms of understanding the ecological aspects associated with invasions, our understanding of the social implications is less obvious (Table 2) (Kueffer, 2013; Vaz et al., 2017a). WfW have funded mostly biological research which is demonstrably necessary and cost-effective, and hydrological and economic research to justify enormous spending on IAP control activities (van Wilgen et al., 1997; McConnachie et al., 2012; van Wilgen and Wannenburgh, 2016). The current body of research came about because (1) the CSIR provided the initial justification for the establishment of WfW, and have received further research funding to improve the understanding of how to develop the programme (Magadlela and Mdzeke, 2004; van Wilgen and Wannenburgh, 2016); (2) there was a long-standing programme, with research capacity and real issues to address, in the ARC PPRI (Plant Protection Research Institute) biological control program, which was an immediate and clear place to invest research funding (Zimmermann et al., 2004); and (3) the establishment of the C·I·B created a hub of activity in the field of invasion biology, with the explicit goal of producing science graduates and research papers (van Wilgen et al., 2014). However, a greater effort must be made to establish a core group of social researchers and incorporate social research into this body of research to more effectively address the socio-ecological challenges associated with biological invasions.

We therefore recommend that a joint, mutually acceptable research strategy be developed that leverages the potential in the PPRI, CSIR, C·I·B and elsewhere to address more complex challenges posed by biological invasions and their management. This is particularly important since the last dedicated research strategy was produced and published 13 years ago (WfW, 2005). More research with applied goals, stakeholder and implementer involvement can be achieved when different funding and research bodies collaborate. This will, however, present funding and research organizations with difficult choices, such as how research resources are pooled, how governance structures are co-developed, how data management and archiving is implemented, and how disciplinary contributions are balanced to avoid asymmetry, such as between social and natural sciences (Holm et al., 2013; Lyall et al., 2013). These collaborations may have implications on the organizations' own structures and procedures, particularly where they are not geared towards, integrative research (Cornell et al., 2013).

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jenvman.2018.06.051.

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